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HYPERSONIC FLIGHT TEST WINDOWS FOR TECHNOLOGY DEVELOPMENT TESTING

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Final Report

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This paper presents hypersonic flight test windows for conducting technology development tests. The SBIR topic AF141-081 titled "Launch Vehicle Systems Intended to Execute Suppressed Trajectories for Hypersonic Testing" can make use of these test windows for developing new launch systems. Four test windows are presented for propulsion and controls, aeroheating, boundary layer, and rocketback using parameters related to those test windows. Each test window is defined by altitude and Mach number so that it is clear what flight conditions new launch systems must achieve.

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NOMENCLATURE

AFRL	Air Force Research Laboratory
BTU	British Thermal Units
ft	foot
HIFiRE	Hypersonic International Flight Research and Experimentation
ISR	Intelligence, Surveillance, and Reconnaissance
kft	kilo-feet (1000's of feet)
psf	pound per square foot
$\dot{Q}$	Heat Rate (BTU/ft^2-sec)
ρ	Atmospheric Density
ρ_{SL}	Atmospheric Density at Sea Level
SBIR	Small Business Innovation Research
sec	seconds

1.0 INTRODUCTION AND BACKGROUND

The Air Force Research Laboratory (AFRL) has been pursuing a variety of technologies to develop hypersonic vehicles for a variety of missions. These missions include high-speed strike, space access, and penetrating intelligence, surveillance, and reconnaissance (ISR). Since replicating hypersonic test conditions on the ground can be very expensive and only have some ability to validate hypersonic technologies, AFRL has conducted and is making plans for technology verification and validation flight tests that include the HIFiRE[1] program and X-51. The data from these flight tests are needed to calibrate computer models and used to make decisions about potential upcoming vehicle development efforts.

Hypersonic vehicles for military purposes often times require advanced technologies in the disciplines that include propulsion, autonomous controls, aerodynamic shaping, and thermal protection. Testing of these technologies can require a wide range of test windows to match parameters including Mach number, Reynolds number, dynamic pressure, and heat rate.

For the flight tests of HIFiRE 1[2], HIFiRE 2[3], and X-51[4], off the shelf and surplus solid rocket motors were used to get the test payloads into the desired test conditions. The upcoming HIFiRE 6[5] flight is using the same solid motor stack as HIFiRE 2. While the acquisition of these solid motors was done at very low to modest cost, significant integration costs and schedule time were needed to be able to launch them in such a way as to meet the goals of a particular test. They also severely limit the amount of control parameters during the boosting flight. For example, the launch system for the HIFiRE 2 test only had three methods of control: the angle of launch and the trigger criteria for the two staging events. It is desirable to allow for increased mission flexibility at a best value to the testing organization while avoiding long development schedules for launch systems. The ability to robustly repeat flight experiments is also desired.

This paper will present desired hypersonic test windows for testing different disciplines of hypersonic technology. The information presented in this paper is meant to help guide the fiscal year 2014 Air Force Small Business Innovative Research (SBIR) solicitation titled “Launch Vehicle Systems Intended to Execute Suppressed Trajectories for Hypersonic Testing”, which is SBIR number AF141-081[6].

2.0 HYPERSONIC TEST WINDOWS

The hypersonic test windows are presented in two ways. The first is a flight condition parameter relevant to the test window versus Mach number. The other is on an altitude vs. velocity chart. The 1962 U.S. Standard Atmosphere was assumed[7] to generate the altitude versus Mach number charts.

The test window charts do not include parameters such as angle of attack, sideslip, and vehicle geometry that are specific to certain missions and vehicle concepts. To allow for the development of launch systems with the greatest amount of flexibility, only those parameters that translate to altitude and velocity are used.

2.1 Propulsion and Controls Test Window

The technologies dealing with scramjet propulsion (inlets, fuel injection, etc.) and hypersonic autonomous control systems are very dependent on the freestream Mach number and dynamic pressure. The Mach number changes the flow characteristics such as shock waves over the geometric features like inlets, causing changes in the pressure distributions. This pressure change can cause rapid changes in aerodynamic moments that the autonomous control system must account for. The pressure changes also affect the inlet recovery and capture area as well as the flow through the scramjet's isolator and combustor. Dynamic pressure is a major contributor to the ability to produce thrust. It is also an important parameter when calculating longitudinal and lateral dynamic modes[8].

This test envelope is shown in Figure 1 and Figure 2. During propulsion tests, it is usually desirable to hold a constant dynamic pressure. Another potential test of interest is to address the technical challenge of when a hypersonic vehicle transitions from acceleration to cruise where there can be large decreases in dynamic pressure.

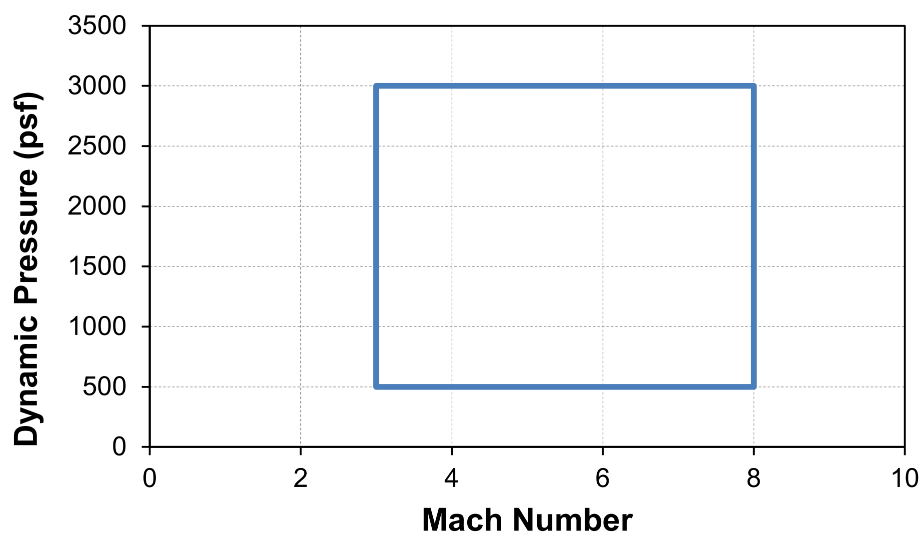

Figure 1. Propulsion and Controls Test Window, Dynamic Pressure vs. Mach Number

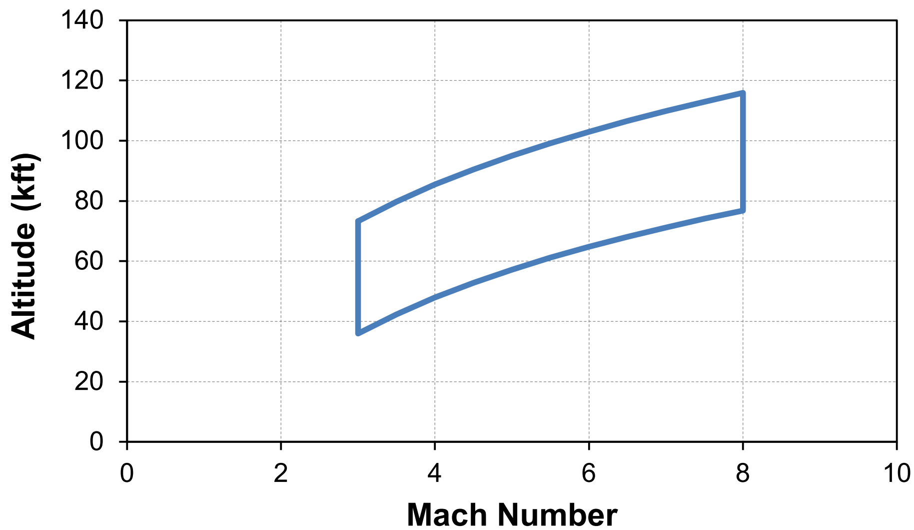

Figure 2. Propulsion and Controls Test Window, Altitude vs. Mach Number

2.2 Hypersonic Boundary Layer Test Window

One of the most difficult challenges in predicting the aerodynamic properties of a hypersonic vehicle is the ability to find the point where boundary layer transitions from laminar to turbulent. This prediction is very important to control drag and heat rates on the vehicle.

The boundary layer test window defined here is bound by the unit Reynolds number versus Mach number and is shown in Figure 3 and Figure 4. Flights through this test window could happen similar to HIFiRE 1 where the unit Reynolds number is constantly changing. Another flight of interest could be attempting to hold a constant unit Reynolds number while changing vehicle orientation like angle of attack.

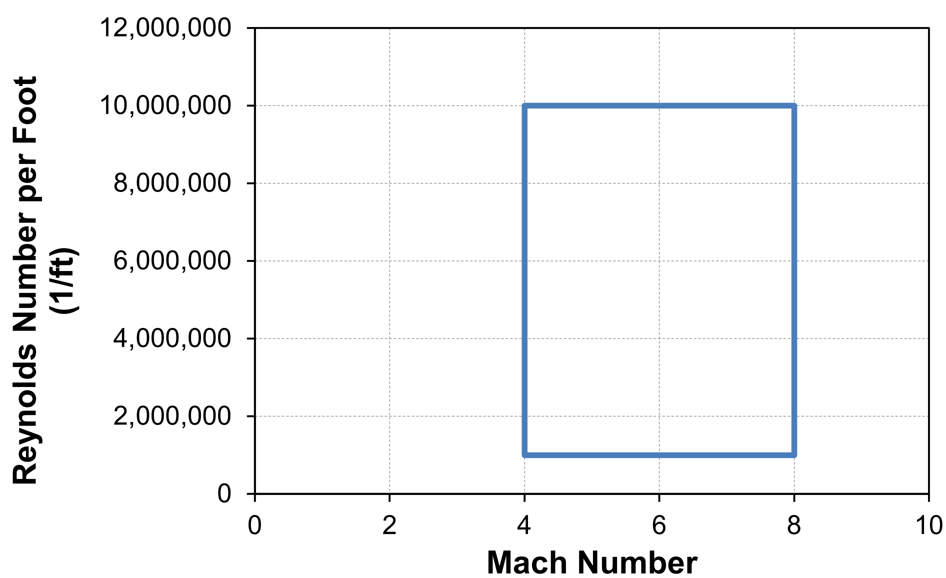

Figure 3. Boundary Layer Test Window, Unit Reynolds Number vs. Mach Number

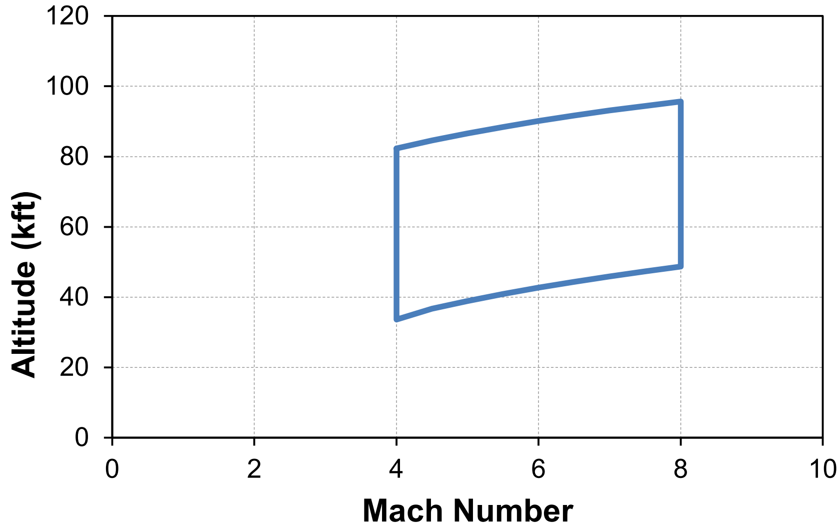

Figure 4. Boundary Layer Test Window, Altitude vs. Mach Number

2.3 Aeroheating Test Window

Designing hypersonic vehicles requires the application of a significant amount of thermal protection or use of a hot structures concept, which can be a major cost driver and technology risk. Testing thermal protection materials can be done in ground test facilities but there are some aspects that require flight testing, such as proper oxidation conditions. Furthermore, properly estimating aeroheating can benefit greatly from in-flight measurements, which will drive the thermal protection system. The test window for aeroheating defined here is based on a reference 1 ft radius sphere and Mach numbers. The heating rate is based on the Chapman equation, shown in equation 1. The test window is shown in Figure 5 and Figure 6. This test window has the largest range of flight conditions presented in this paper.

$$\dot{Q} = 17600\left(\frac{\rho}{\rho_{SL}}\right)^{\frac{1}{2}}\left(\frac{Velocity}{26000ft/sec}\right)^{3.15}$$

$$\rho = Density \tag{1}$$

$$\dot{Q}\ is\ in\ BTU/(ft^2 * \mathrm{s})$$

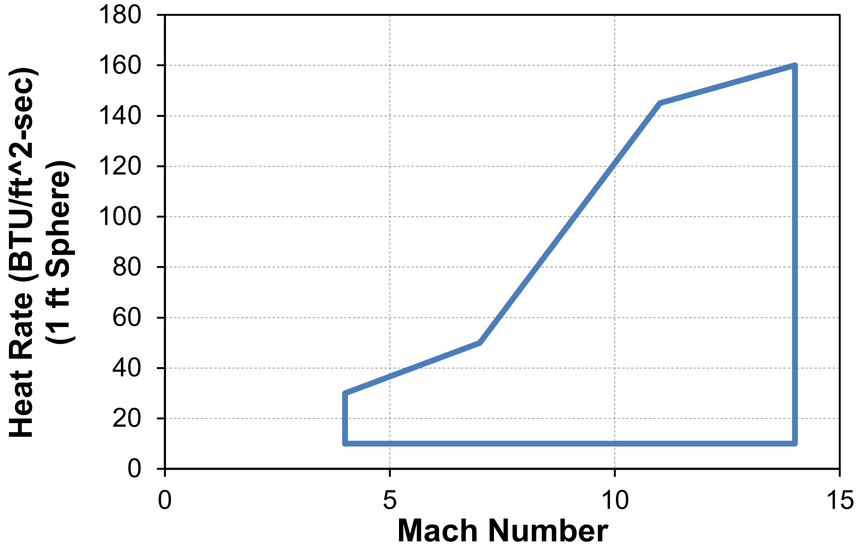

Figure 5. Aeroheating Test Window, Heat Rate vs. Mach Number

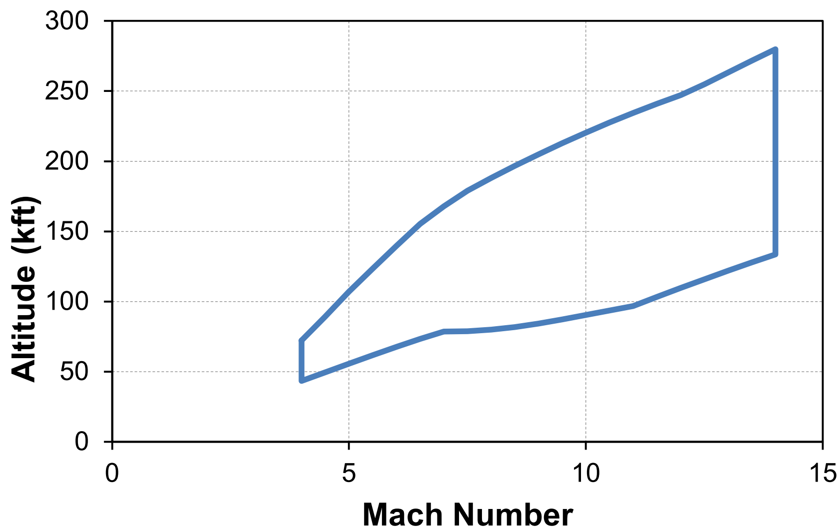

Figure 6. Aeroheating Test Window, Altitude vs. Mach Number

2.4 Rocketback Test Window

The Reusable Booster System Pathfinder program run by AFRL was attempting to demonstrate the rocketback trajectory for next generation access to space[9]. Part of that program was to better define the test window needed to properly validate aerodynamic and design models for designing an operational vehicle utilizing rocketback. The flight test window from that effort was defined by dynamic pressure and Mach number but significantly different from the above mentioned propulsion and controls test window. The rocketback maneuver requires total angles of attack (ε) above 90º while passing through the flight conditions of the rocketback test window. Figure 7 and Figure 8 depict this test window.

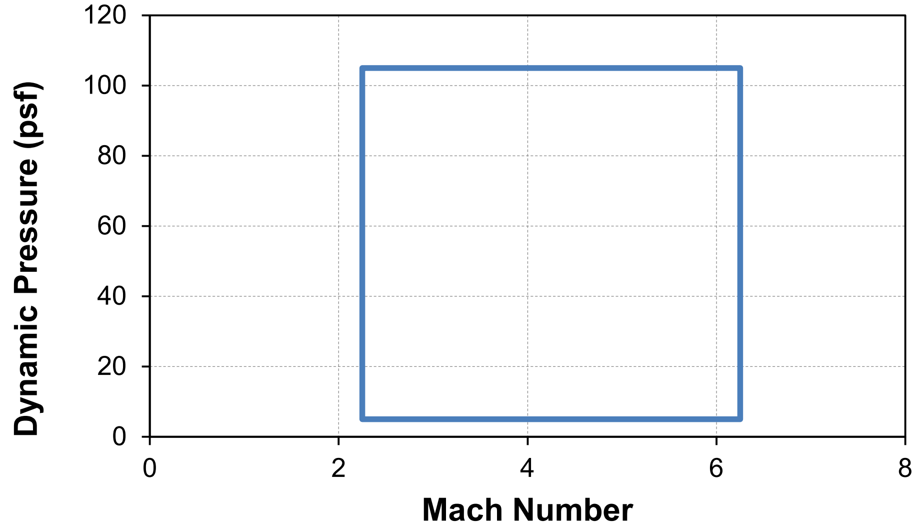

Figure 7. Rocketback Test Window, Dynamic Pressure vs. Mach Number

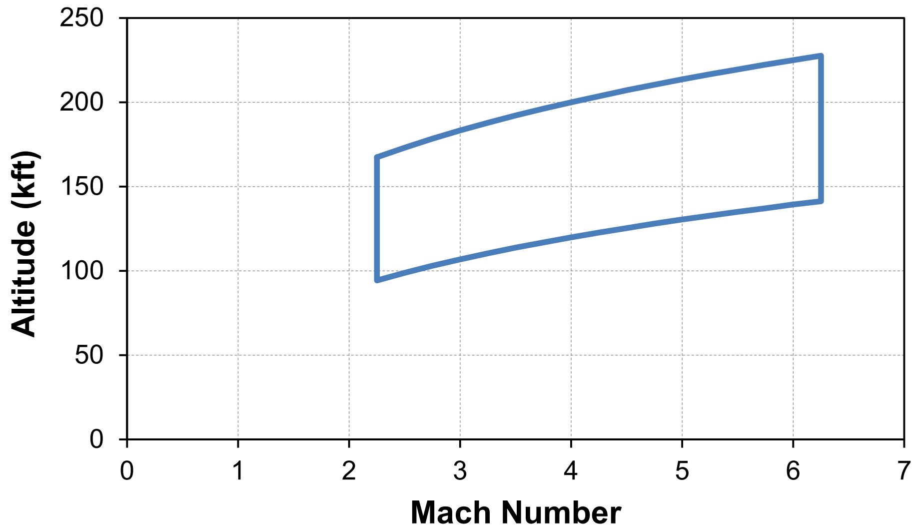

Figure 8. Rocketback Test Window, Altitude vs. Mach Number

2.5 Comparison of All Test Windows

Figure 9 compares all the test windows presented in this paper. There is some overlap especially between Mach 4 and 8 and around 75 kft to 125 kft in altitude. From this overlap, it could be reasoned that these flight conditions are very important to developing hypersonic technologies. A flight experiment that flies through these conditions could gather test data related to a wide variety of technologies.

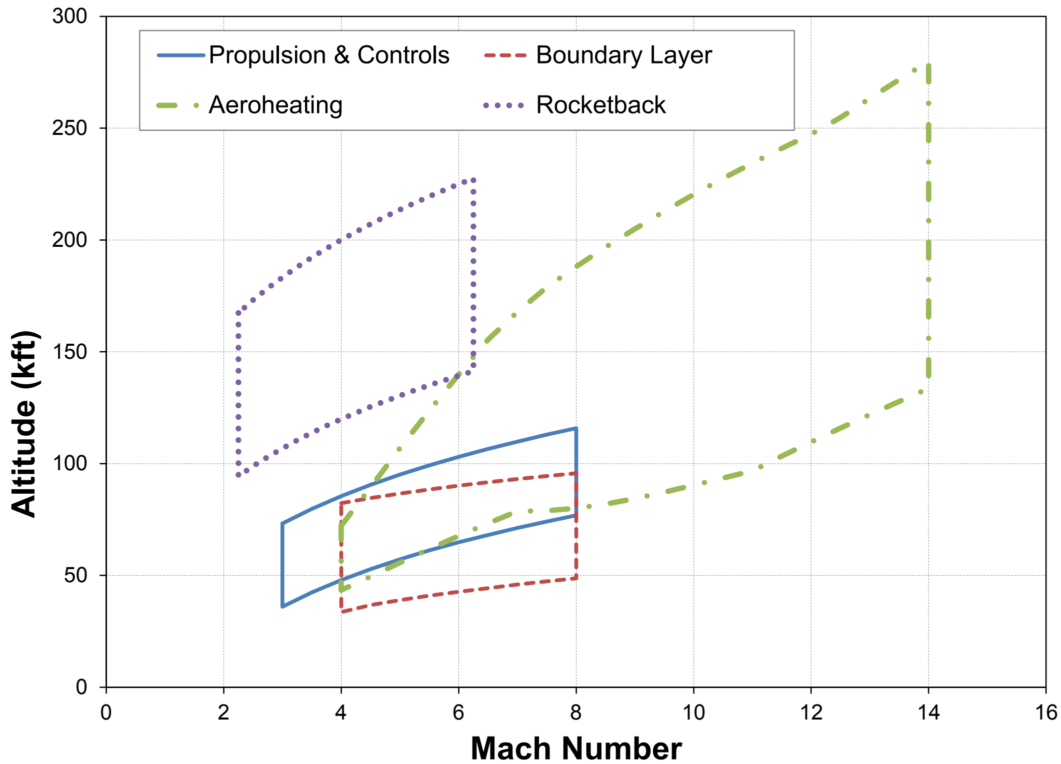

Figure 9. Comparison of All Test Windows Plotted as Altitude vs. Mach Number

3.0 LAUNCH SYSTEMS FOR HYPERSONIC TEST WINDOWS

The current approach to test in these hypersonic test windows from the HIFiRE program has mostly been focused on using solid rocket motors. This approach limits the amount of control parameters to tailor the trajectory. Also, the solid motors have shown to be more costly and require schedule lengths longer that originally expected. Newer systems to support flight tests in these test windows are desired be more cost effective, i.e. provide significant cost savings over current capability and/or provide more ability and flexibility to design a flight test experiment. The ability to provide more timely tests is also desired.

The desired capabilities of new launch systems while taking into account the expense to execute a flight test include:

- Reduction of software verification & validation
- Simplification in meeting test range safety requirements
- Simplification in test range integration
- Reduction of uncertain flight environments (e.g. transonic)
- Reduction in stages
- Reduction in additional hardware
- Reduction of undesirable loads on the payload
- Maximization of test time
- Reduction of ground infrastructure and personnel
- Reduction in aerodynamic loads (during boost)
- More vertical launch direction (not applicable to air-launched systems)

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